RESEARCH

1(2), April - June, 2015

ISSN 2394–8558
EISSN 2394–8566

Climate Change

Earthquake triggering rainfall in Taiwan

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Article History
Received: 23 December 2014
Accepted: 30 January 2015
Published: 1 April 2015

Citation
Jyh-Woei, Lin. Earthquake triggering rainfall in Taiwan. *Climate Change*, 2015, 1(2), 72-82

ABSTRACT

This study objectively investigates the potential of rainfall to trigger earthquakes. Earthquakes (ML >3.0) and rainfall from 1995 to 2012 were examined in Taiwan. The earthquakes have a significant positive relationship with rainfall after the 1999 Chi-Chi earthquake as demonstrated using the Chi-square test. The results reveal a significant difference between the correlations for daily accumulated rainfall values and earthquake frequency before and after the Chi-Chi earthquake. The significant difference is discussed in regards to changes of geological conditions after the Chi-Chi earthquake.

Keywords: Trigger, Chi- earthquake, Earthquake activity, Chi-square test.

1. INTRODUCTION

The topic of rainfall-induced earthquakes has been researched in the past. Husen et al. (2007) reported a series of 47 local earthquakes in the central Switzerland Alps that occurred three days after record rainfall during August 19–23, 2005. Healy et al. (1968) conducted a study in Denver, Colorado where liquid waste was injected into geological faults resulting in increased seismicity. While this trigger mechanism seems to be unlikely for deep earthquakes, it is possible that changes in geological conditions such as level and pressure variances in groundwater due to heavy rainfall (Saar and Manga, 2003; Yeh et al., 2008) may affect the deep subterranean environments. For example, water from rainfall may change groundwater levels in shallow layers near the ground surface while simultaneously inducing slight stress and pressure redistributions near the deep faults according to the Mohr–Coulomb failure criterion (Hoek et al., 2002), and this could potentially trigger large earthquakes even though their depths are large. Lin' work (2014) researched the triggering relations between the rainfalls and the earthquakes that have small magnitude with 1<ML<2 and with the depth < 5km.

In this study, a statistical analysis (Chi-square test) of earthquakes (ML >3.0, with the depth < 100km) on the island of Taiwan between 1995 and 2012 was used to test for the possibility of rainfall-triggering earthquakes.

2. METHOD

A Chi-square test was conducted to confirm the correlation between two independent data sets, and an asymptomatic significance value (p-value) was then used to determine the significant difference and strength of the relationship between the two data sets; differences were deemed significant when the p-value was equal to or smaller than 0.05 (5%), (Bewick et al., 2004). For the two independent data sets, the Chi-square test was computed is based on calculating the variance of each data set with n components ($x_1, x_2 .... x_n$) using the formula $\frac{\sum_{i-1}^{n}(x_i - \overline{X})^2}{n-1}$, where the denominator (n – 1) and $\overline{X}$ are the degrees of freedom and mean of the data set, respectively, and estimates of p-values were derived for the distribution of $\overline{X}$, Let $E(\overline{X}) = \mu$ and $Var(\overline{X}) = \frac{\sigma^2}{n}$, and thus $\overline{X} \sim N\left(\mu, \frac{\sigma^2}{n}\right)$. To calculate the desired probability $P(\overline{X} > \overline{x}) = P\left(\frac{\overline{X}-\mu}{\sigma/\sqrt{n}} > \frac{\overline{x}-\mu}{\sigma/\sqrt{n}}\right) = P\left(Z > \frac{\overline{x}-\mu}{\sigma/\sqrt{n}}\right)$, this probability is the p-value. (Lawrence et al. 2006).

3. DATA SOURCE

The daily average-accumulated rainfall values are the averages of the rain gauge stations near the epicenters of the earthquakes and the earthquake activity located offshore of Taiwan is not considered. The true monthly accumulated rainfall values are the multiple of 28, 30 or 31 (days) for the daily average-accumulated rainfall values (a month period). The true monthly accumulated rainfall values were also used by Chi-square test, the results were the same as using the daily average-accumulated rainfall values, and however the computing time is much more. Thus the daily average-accumulated rainfall values were used due to almost same period of a month (28, 30 or 31 (days) for a month period) (http://www.cwb.gov.tw/eng/index.htm).

4. DATA ANALYSIS AND RESULTS

The difference in the correlations between daily rainfall and earthquake activity before and after the Chi-Chi earthquake (for the two data sets in Table 1 and Table 2 before and after the Chi-Chi earthquake, respectively) was determined by a Chi-square test. Figure 1 shows the correlations between the daily accumulated rainfall (R) (top figure) and the number of earthquakes (ML >3.0) in a month (N) (bottom figure) before the Chi-Chi earthquake (data are from Table 1). The curves of both figures are not correlated, and this means that the peak values of both curves are not consistent as opposed to the data in Figure 2 after the Chi-Chi earthquake (i.e. data from Table 2), which are fairly consistent. From these data, it seems likely that there is a significant difference for the relationships between rainfall and seismic activity before and after the Chi-Chi earthquake. Using the Chi-square test, the p-value was estimated to be nearly 4.86×10^{-12} , which is less than 0.05, and therefore a strong significant difference exists between the both relationships (Bewick et al., 2004) for the two data sets before and after the Chi-Chi earthquake. It means that the relationship of rainfall and seismic activity before Chi-Chi earthquake is less than the relationship of rainfall and seismic activity after Chi-Chi earthquake. Specifically, increased earthquake activity was found to be associated with heavy rainfall after the Chi-Chi earthquake but not before it. Figure 3 shows the relationship between the number of the earthquakes in a month (N) and the daily-accumulated rainfall (R) along with the results of the Chi-square test. Both circles and crosses indicate the N–R relationships before and after the Chi-Chi earthquake, respectively. The 'circle' symbols indicate the daily accumulated rainfall and the corresponding number of earthquakes in a certain month before the Chi-Chi earthquake (it is very difficult to show the dependence of earthquake activity on rainfall before the Chi-Chi earthquakes with the circles because of their large spread along both axes). The 'cross' symbols indicate the daily accumulated rainfall and the corresponding number of earthquakes in a certain month after the Chi-Chi earthquake (the crosses show the dependence of earthquake activity on rainfall after the Chi-Chi earthquake, and these had a relatively small spread along both axes). Due to the use of the log-scale, the correlation of N–R in the regression line after the Chi-Chi earthquake was large, and the before and after trends showed opposite patterns. Specifically, the best-fitted equation for the N–R regression before the Chi-Chi earthquake was

$$LogN = 2.000 - 0.168\,LogR\,. \quad (1)$$

In contrast, the best-fitted equation for the N–R regression after the Chi-Chi earthquake was

$$LogN = 2.021 + 0.343\,LogR\,. \quad (2)$$

Table 1

This table lists the earthquake activity related to daily accumulated rainfall values from January 1995 to September 1999 (Source: Central Weather Bureau, Taiwan). Note: The daily accumulated rainfall values are the averages of the rain gauge stations near the epicenters of the earthquakes and the earthquake activity located offshore of Taiwan is not considered.

Year	Month	Earthquake Number	Daily accumulated rainfall values
1995	1	5	22.0mm
1995	2	4	50.0mm
1995	3	4	49.0mm
1995	4	6	70.0mm
1995	5	12	40.0mm
1995	6	5	300.0mm
1995	7	8	70.0mm
1995	8	3	100.5mm
1995	9	1	120.0mm
1995	10	3	20.5mm
1995	11	13	26.5mm
1995	12	5	30.5mm
1996	1	7	10.0mm
1996	2	6	100.0mm
1996	3	1	50.5mm
1996	4	4	48.5mm
1996	5	2	32.8mm
1996	6	3	80.5mm
1996	7	4	90.5mm
1996	8	3	100.5mm
1996	9	4	70.0mm
1996	10	3	40.5mm
1996	11	5	30.4mm
1996	12	3	10.5mm
1997	1	8	60.0mm
1997	2	4	22.5mm
1997	3	4	63.5mm

1997	4	3	68.0mm
1997	5	2	55.0mm
1997	6	6	33.5mm
1997	7	3	35.0mm
1997	8	5	60.0mm
1997	9	3	35.5mm
1997	10	3	40.5mm
1997	11	7	55.5mm
1997	12	3	32.5mm
1998	1	6	34.0mm
1998	2	4	75.0mm
1998	3	3	43.5mm
1998	4	4	41.5mm
1998	5	6	48.5mm
1998	6	3	36.5mm
1998	7	8	47.0mm
1998	8	2	45.0mm
1998	9	5	120.5mm
1998	10	2	100.5mm
1998	11	7	28.5mm
1998	12	5	30.0mm
1999	1	6	20.5mm
1999	2	4	10.0mm
1999	3	2	20.5mm
1999	4	4	70.5mm
1999	5	8	60.5mm
1999	6	3	40.5mm
1999	7	7	12.0mm
1999	8	8	102.5mm
1999	9	90	140.5mm

Table 2
This table shows the earthquake activity related to daily accumulated rainfall values from October 1999 to August 2012 and these data condition is the same as those of Table 1.

Year	Month	Earthquake Number	Daily accumulated rainfall value
1999	10	93	40.0mm
1999	11	34	20.0mm
1999	12	17	30.0mm
2000	1	13	45.0mm
2000	2	10	3.0mm
2000	3	17	20.0mm
2000	4	14	20.5mm
2000	5	50	300.5mm

2000	6	59	320.5mm
2000	7	60	434.0mm
2000	8	70	481.5mm
2000	9	51	294.0mm
2000	10	84	500.5mm
2000	11	29	20.5mm
2000	12	40	20.0mm
2001	1	30	100.0mm
2001	2	40	150.0mm
2001	3	25	26.5mm
2001	4	15	28.5mm
2001	5	15	11.8mm
2001	6	60	324.5mm
2001	7	15	12.5mm
2001	8	23	28.5mm
2001	9	33	95.0mm
2001	10	21	15.5mm
2001	11	20	30.4mm
2001	12	23	40.5mm
2002	1	14	3.0mm
2002	2	10	30.0mm
2002	3	36	40.5mm
2002	4	50	408.0mm
2002	5	60	320.0mm
2002	6	40	300.5mm
2002	7	19	45.0mm
2002	8	37	267.0mm
2002	9	27	47.5mm
2002	10	71	300.5mm
2002	11	17	50.5mm
2002	12	19	40.5mm
2003	1	18	24.0mm
2003	2	21	65.0mm
2003	3	16	23.5mm
2003	4	21	340.5mm
2003	5	20	40.5mm
2003	6	38	60.5mm
2003	7	24	30.0mm
2003	8	22	15.0mm
2003	9	24	29.5mm
2003	10	25	22.5mm
2003	11	21	28.5mm
2003	12	80	470.0mm
2004	1	26	44.5mm
2004	2	28	50.0mm
2004	3	21	34.5mm
2004	4	17	110.5mm
2004	5	47	290.5mm
2004	6	13	30.5mm

2004	7	17	120.0mm
2004	8	19	90.0mm
2004	9	16	80.5mm
2004	10	20	40.5mm
2004	11	28	70.5mm
2004	12	9	4.5mm
2005	1	43	70.5mm
2005	2	67	390.0mm
2005	3	50	370.5mm
2005	4	77	389.0mm
2005	5	106	397.5mm
2005	6	52	140.0mm
2005	7	29	133.0mm
2005	8	22	50.5mm
2005	9	20	22.0mm
2005	10	33	4.0mm
2005	11	20	6.0mm
2005	12	21	20.0mm
2006	1	37	43.0mm
2006	2	29	50.0mm
2006	3	24	120.0mm
2006	4	81	400.5mm
2006	5	17	49.0mm
2006	6	36	49.0mm
2006	7	21	33.0mm
2006	8	35	46.0mm
2006	9	19	28.5mm
2006	10	27	43.0mm
2006	11	29	40.0mm
2006	12	47	204.5mm
2007	1	31	200.0mm
2007	2	44	240.5mm
2007	3	50	30.0mm
2007	4	37	200.0mm
2007	5	26	40.0mm
2007	6	40	200.0mm
2007	7	31	220.0mm
2007	8	37	190.0mm
2007	9	40	345.0mm
2007	10	29	240.0mm
2007	11	28	13.0mm
2007	12	28	20.0mm
2008	1	22	30.0mm
2008	2	49	100.0mm
2008	3	32	90.5mm
2008	4	50	254.5mm
2008	5	37	59.0mm
2008	6	39	50.0mm
2008	7	45	250.5mm

2008	8	58	300.5mm
2008	9	26	30.0mm
2008	10	29	40.5mm
2008	11	47	100.0mm
2008	12	30	90.5mm
2009	1	49	100.5mm
2009	2	31	80.0mm
2009	3	40	100.0mm
2009	4	27	100.0mm
2009	5	27	50.0mm
2009	6	130	480.0mm
2009	7	119	367.0mm
2009	8	57	400.0mm
2009	9	29	200.5mm
2009	10	62	100.0mm
2009	11	60	80.0mm
2009	12	92	100.0mm
2010	1	26	20.5mm
2010	2	20	46.0mm
2010	3	69	280.0mm
2010	4	48	300.0mm
2010	5	31	180.0mm
2010	6	39	100.5mm
2010	7	40	400.0mm
2010	8	47	270.0mm
2010	9	73	300.0mm
2010	10	93	330.0mm
2010	11	76	200.0mm
2010	12	35	18.5mm
2011	1	38	12.5mm
2011	2	52	300.5mm
2011	3	71	500.0mm
2011	4	53	220.0mm
2011	5	54	40.0mm
2011	6	49	50.0mm
2011	7	91	600.0mm
2011	8	45	200.5mm
2011	9	53	90.0mm
2011	10	46	80.0mm
2011	11	56	120.0mm
2011	12	45	130.0mm
2012	1	107	400.0mm
2012	2	60	280.0mm
2012	3	60	370.0mm
2012	4	39	60.0mm
2012	5	56	50.0mm
2012	6	160	900.0mm
2012	7	49	500.5mm
2012	8	70	100.5mm

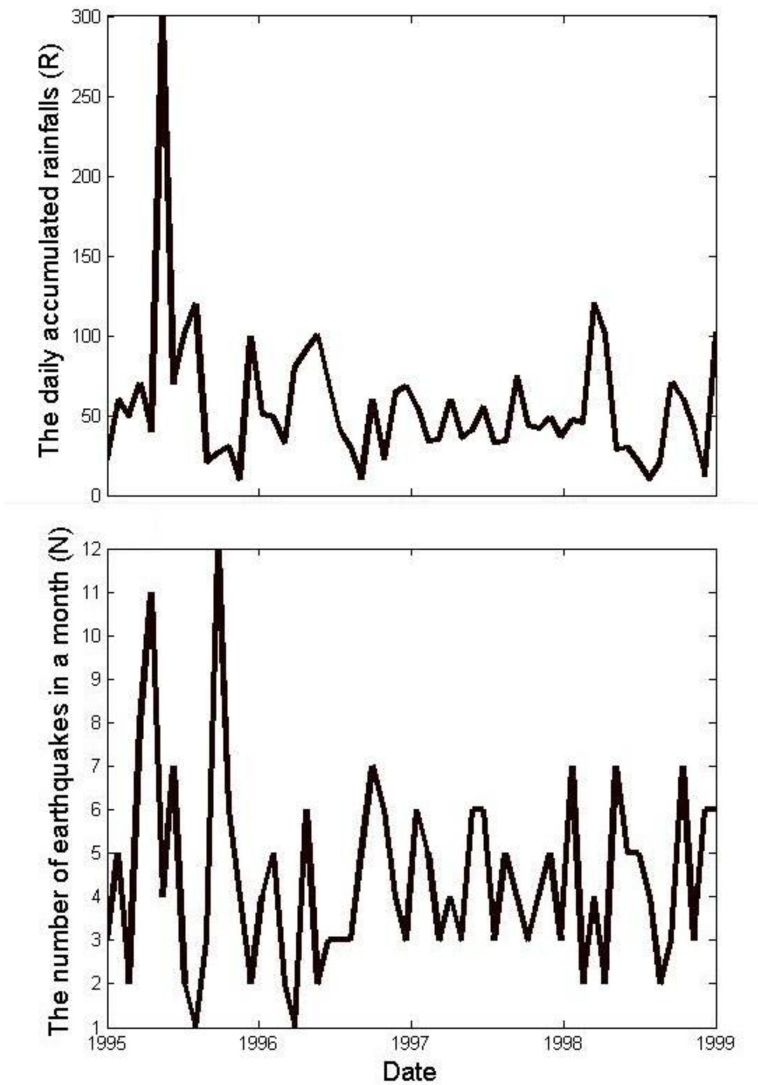

Figure 1

This figure set shows the variations in daily accumulated rainfalls (R) (Top figure) and the number of earthquakes (ML >3.0) in a month (N) (Bottom figure) before the Chi-Chi earthquake. The curves of both figures hove are not correlated that means that the peak values of both curves are not consistent.

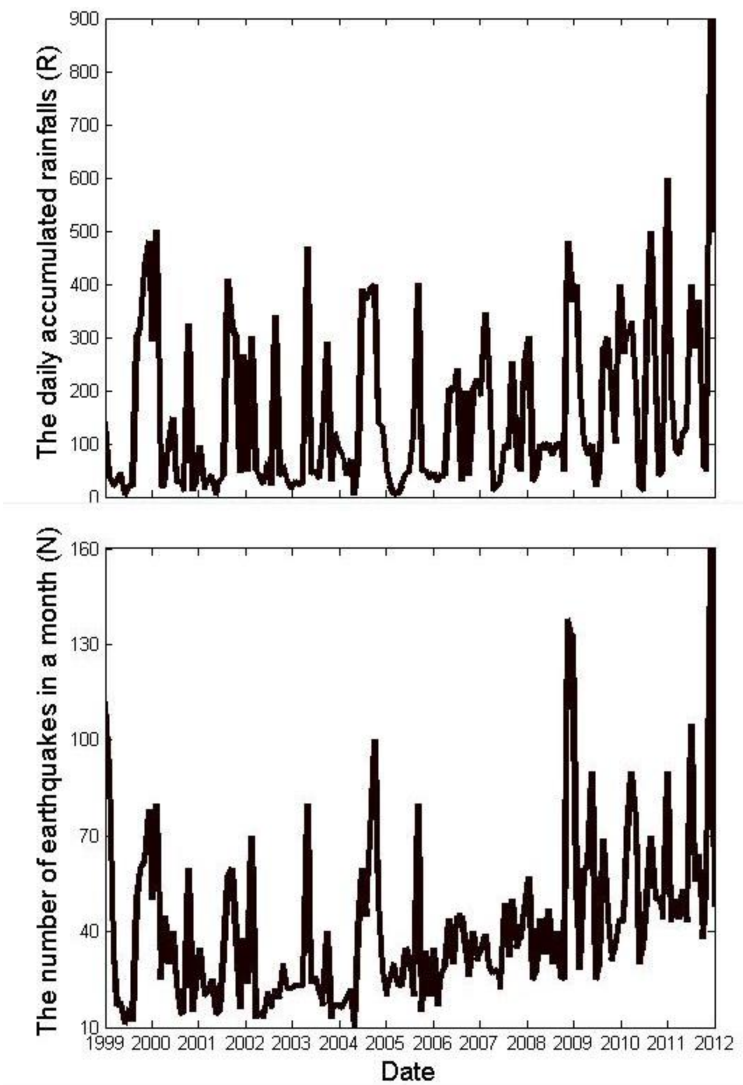

Figure 2

This figure set shows the variations in daily accumulated rainfalls (R) (Top figure) and the number of earthquakes (ML >3.0) in a month (N) (Bottom figure) after the Chi-Chi earthquake. The curves of both figures are well correlated that means that the peak values of both curves are more consistent.

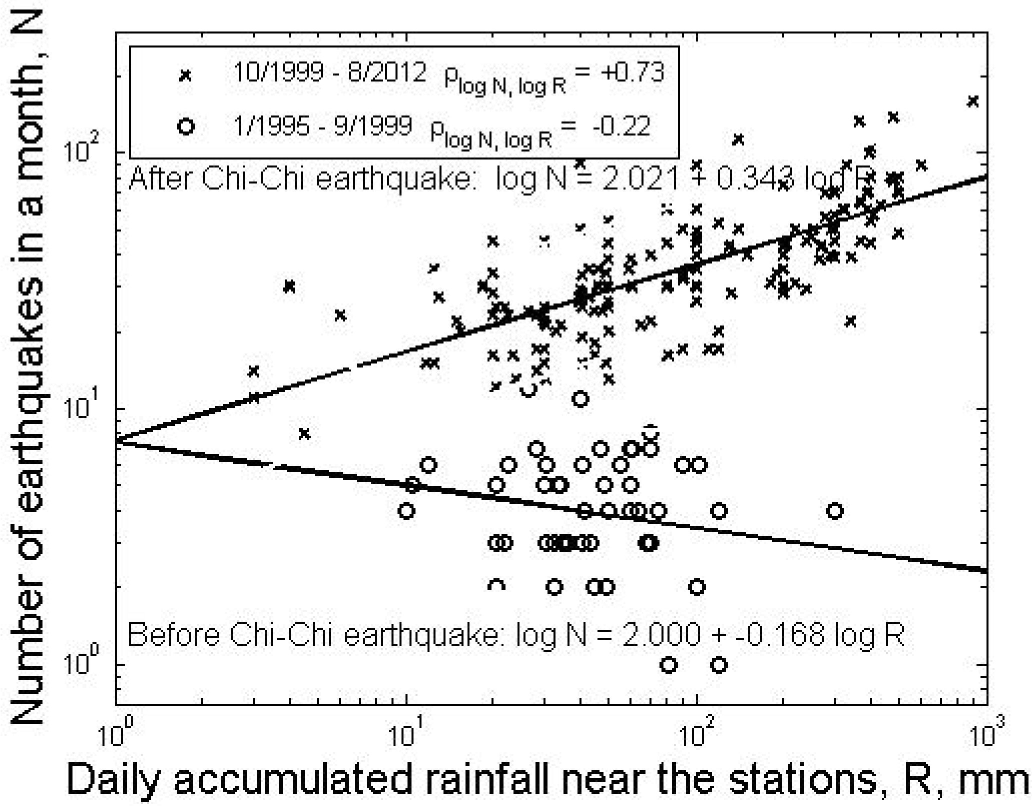

Figure 3

This figure shows the correlations between the number of earthquakes (ML >3.0) in a month (N) and the daily accumulated rainfalls (R) before and after the Chi-Chi earthquake (Note in log-scale for both horizontal (R) and perpendicular (N) axes).

5. DISCUSSION

The correlation was low, with a slightly negative coefficient of –0.22, before the Chi-Chi earthquake according to Eq. (1). Therefore, earthquake activity was negatively associated with heavy rainfall during this period, but only slightly. In contrast, the correlation was high, with a positive coefficient of +0.73, after the Chi-Chi earthquake according to Eq. (2). During this period, earthquake activity increased during times of heavy rainfall. These results, which cover a period from 1995 to 2012, include earthquake activity both before and after the Chi-Chi earthquake. The Chi-Chi earthquake may have resulted in geologically significant changes throughout Taiwan that made the area more susceptible to subsequent rainfall-triggered earthquakes. For example, the earthquake could have formed some blind faults (Tsou et al., 2011; Neïla Zarrouk, Raouf Bennaceur, 2015) and activated existed old faults. This may have then resulted in changes in the level and pressure of groundwater during heavy rainfall and caused slight stress and pressure redistributions near the deep faults. Such a situation could allow rainfall to trigger earthquakes. Hence, further investigations of rainfall-induced earthquakes in Taiwan are warranted to rule out alternative hypothesis for the increase in seismicity.

6. CONCLUSION

This study found that the relationship between daily rainfall and earthquake activity before and after the Chi-Chi earthquake was significantly different. Increased earthquake activity was found to be associated with heavy rainfall after the Chi-Chi earthquake but not before it. It is possible that changes caused by the Chi-Chi earthquake made geological conditions more suitable for subsequent rainfall-triggered earthquakes.

ACKNOWLEDGEMENT

The author is grateful to Central Weather Bureau, Taiwan for the data support.

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